Measuring the two-photon exchange amplitude with vector analyzing powers in elastic electron-proton scattering

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Abstract

We propose to measure the vector analyzing power, or beam normal spin asymmetry, in inclusive elastic electron-proton scattering at beam energies of 0.424, 0.585, and 0.799 GeV and at laboratory electron scattering angles of 110°, corresponding to Q^2 values of 0.3, 0.5, and 0.8 (GeV/c)^2, respectively, using the G0 apparatus in its backward angle mode. The vector analyzing power in elastic scattering with a transversely polarized electron beam is a time reversal odd observable which must vanish in the single photon exchange approximation. This observable is directly proportional in leading order to the imaginary part of the two photon exchange amplitude, the real part of which has been proposed as a possible resolution to the descrepancy between Rosenbluth separation and polarization observable measurements of the ratio of the electric to magnetic proton form factors. Recent calculations tie this observable to resonance region treatments of box diagrams and generalized parton distributions. The G0 apparatus is designed specifically to measure small yield asymmetries, and the kinematics of the backward angle measurements are ideal for observing maximum effects from the two photon exchange amplitude to this observable.

1 Introduction

Recently the experimental precision with which electromagnetic form factors of the proton have been determined over a wide range of momentum transfers has called into question some of the original assumptions about the reaction mechanism used to extract these quantities. While it is known that single virtual photon exchange between the electron and the proton dominates the reaction, and the two photon exchange contribution is of order a few percent, the experiments have pushed the precision to this level. Experimentally, this has manifested itself in the comparison of the determination of the ratio of the electric to magnetic proton form factors, G_E^p/G_M^p, as a function of Q^2 through two different methods: the "standard" method of a Rosenbluth separation of G_E^p and G_M^p through cross section measurements in different kinematics at the same Q^2, and the polarization transfer method which measures the ratio of the scattered proton's transverse to longitudinal polarization, also proportional to G_E^p/G_M^p [1, 2, 3]. The descrepancy between the two sets of observables as Q^2 increases has prompted significant theoretical efforts to include the effects of the two-photon exchange contribution, the initial results of which indicate that these effects can explain much of the differences seen by the experiements. Thus, for these observables, the assumption of single photon exchange, or Born approximation, breaks down and two photon exchange effects must be taken into account. It is therefore necessary to find and measure observables which are sensitive to the two photon exchange amplitude to test the validity of the theory.

The vector analyzing power in elastic electron-proton scattering, in which a transversely polarized electron beam is scattered from an unpolarized proton target, is a time reversal odd observable which must vanish in the single photon exchange approximation. This observable is directly proportional to the imaginary part of the two photon exchange amplitude, and its measurement will provide necessary experimental input to constrain these theoretical efforts. Moreover, the imaginary part of this amplitude is interesting in its own right in the context of its physics content in the intermediate state and its implications for box diagrams in general [4], as well as its recently demonstrated connection to generalized parton distributions [5]. While a variety of experiments designed to measure different observables which are also sensitive to the imaginary part of this amplitude are presently being considered, we note that the only direct experimental observation of non-zero two photon exchange effects has been through vector analyzing power measurements.

The first measurement of the vector analyzing power in elastic e-p scattering (and also quasielastic e-d scattering) was performed with a 200 MeV beam at $Q^2 = 0.1$ (GeV/c)^2 at $\theta \sim 146°$, using the SAMPLE apparatus at MIT/Bates [6], resulting in $A_n = -15.4 \pm 5.4$ ppm. This observable was also recently measured with the PVA4 apparatus at Mainz [7] with an 855 MeV beam and $Q^2 = 0.23$ (GeV/c)^2 at $\theta \sim 35°$, resulting in $A_n = -8.0 \pm 2.6$ ppm, and with a 570 MeV beam and $Q^2 = 0.1$ (GeV/c)^2 at $\theta \sim 35°$, resulting in $A_n = -9.6 \pm 1.7$ ppm. The combination of high luminosity and large acceptance detectors in each of these experiments allowed for the observation of these few part per million (ppm) effects in a relatively short amount of beam time. The G0 apparatus [8] is similarly equipped, having high rate capability, a large acceptance, and the ability to measure yield asymmetries at the ppm level. The azimuthal symmetry of the G0 spectrometer and detector system is uniquely ideal for these measurements at Jefferson Lab, where one is interested in an azimuthal variation of the yield asymmetry. In addition, as we show below, the kinematics of the G0 backward angle running are ideal for observing maximum effects of the two photon exchange contribution to this observable.

The members of PAC 25 summarized that the case for a measurement of two photon exchange effects has been driven by the descrepency between different measurement techniques extracting the proton form factor ratios discussed above, and that emphasis should be placed on experiments aimed at measuring the real part of the two photon exchange amplitude which has direct consequences for this ratio. Accordingly, they recommended that the two experiments proposed which were aimed at measuring the imaginary part of the two photon exchange amplitude be deferred until a stronger case could be made for measuring this part of the amplitude.

Recently, calculations of the imaginary part of the two photon exchange amplitude, and corresponding predictions of the vector analyzing power, have been made using a resonance region treatment [4], and another set making a direct connection to the generalized parton distributions [5]. The kinematics of the proposed measurements are well suited to test models based on resonance region treatments, and approach the kinematics where models using generalized parton distributions should be valid. These measurements therefore will provide a basis for comparing theoretical treatments in these two different formalisms in a kinematic regime where the two may overlap.

Experimentally, the proposed measurements have several advantages, including: i) no modification to the G0 backward angle apparatus is required to perform the proposed measurements, ii) transversely polarized beams have been established into Hall C, so beam development for this is not required, iii) the G0 forward angle apparatus has successfully measured vector analyzing powers in both elastic and inelastic electron-proton scattering at the ppm level, and iv) theoretical predictions of the vector analyzing power in the kinematics of the G0 backward angle setup suggest that this kinematic regime has the largest magnitude of this observable, so that statistically significant measurements can be made with a relatively small amount of beam time. The analysis of the forward angle vector analyzing power data is underway.

2 Scientific Justification

2.1 The Vector Analyzing Power: Formalism

The vector analyzing power in elastic electron-hadron scattering results in a spin-dependent asymmetry where the spin-dependence in the scattering cross section $\sigma(\theta)$, can be written as [10, 11]

$$\sigma(\theta) = \sigma_0(\theta)[1 + A_n(\theta)\mathbf{P} \cdot \hat{\mathbf{n}}], \tag{1}$$

where $\sigma_0(\theta)$ is the spin-averaged scattering cross section, $A_n(\theta)$ is the vector analyzing power for the reaction, and $\mathbf{P}$ is the incident electron polarization vector (which is proportional to the spin vector operator $\mathbf{S}$). As shown in

Fig. 1, the unit vector $\hat{\mathbf{n}}$ is normal to the scattering plane, and is defined through $\hat{\mathbf{n}} \equiv (\mathbf{k} \times \mathbf{k}')/|\mathbf{k} \times \mathbf{k}'|$, where $\mathbf{k}$ and $\mathbf{k}'$ are wave vectors for the incident and scattered electrons, respectively. The scattering angle θ is found through $\cos\theta = (\mathbf{k} \cdot \mathbf{k}')/|\mathbf{k}||\mathbf{k}'|$, and, in the Madison convention, is positive for the electron scattering to beam left for $\hat{\mathbf{n}}$ along the vertical (as in Fig. 1). The beam polarization $\mathbf{P}$ can be expressed in terms of the number of beam electrons with spins parallel (m_s=+1/2) and antiparallel (m_s=-1/2) to $\hat{\mathbf{n}}$, so that the measured asymmetry $\epsilon(\theta)$ at a given scattering angle θ in the plane to which $\hat{\mathbf{n}}$ is normal, is defined through

$$\epsilon(\theta) = \frac{\sigma_\uparrow(\theta) - \sigma_\downarrow(\theta)}{\sigma_\uparrow(\theta) + \sigma_\downarrow(\theta)} = A_n(\theta)\langle P_n\rangle, \tag{2}$$

where $\sigma_{\uparrow,\downarrow}(\theta)$ is the differential cross section for $m_s = +1/2$ and -1/2, respectively. Thus, with knowledge of the magnitude of the incident beam polarization $\langle P\rangle$ along the $\hat{\mathbf{n}}$ axis, a measurement of $\epsilon(\theta)$ can yield a determination of the vector analyzing power $A_n(\theta)$, which contains the underlying physics of the electron-hadron interaction. The asymmetry ϵ should therefore vary sinusoidally in ϕ as

$$\epsilon(\theta,\phi) = A_n(\theta) P \sin(\phi + \delta), \tag{3}$$

where A_n is the vector analyzing power for the reaction. With an azimuthally symmetric detector such as the G0 apparatus, which has 8 detector packages positioned at 8 different average values of ϕ, we can extract the vector analyzing power from a fit to the sinusoidal dependence through a χ^2 minimization:

$$\chi^2_{d.o.f.} = \frac{1}{6}\sum_{i=1}^{8}[A_n^i - (a\sin\phi_i + b\cos\phi_i)]^2/[\delta A_n^i]^2, \tag{4}$$

which is linear in the coefficients a and b. Here A_n^i and δA_n^i are the measured asymmetry and error, respectively, at each azimuthal angle ϕ_i, corrected for all effects including beam polarization normalization (as suggested in Eq. (2)). The coefficients a and b can then be converted into an amplitude and phase, i.e.,

$$A_{fit} = |A_n|\sin(\phi + \delta) \tag{5}$$

as in Eq. (3), where the amplitude $|A_n|$ gives the magnitude of the vector analyzing power, and the phase δ verifies the direction of the beam polarization and determines the overall sign of the analyzing power.

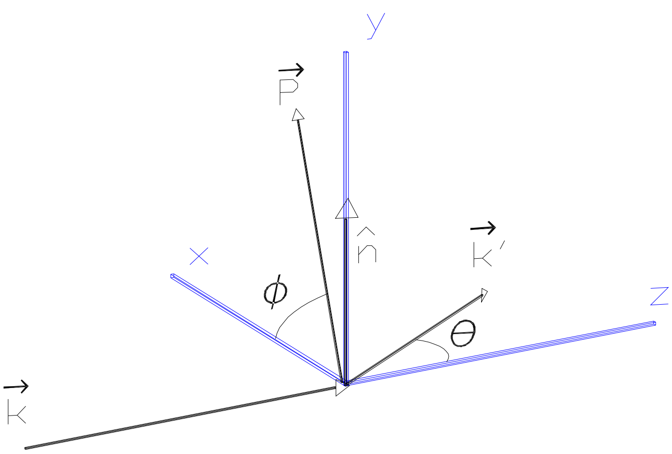

Figure 1: Schematic of the vectors associated with transverse polarization measurements. Shown are the incident and scattered electron wave vectors, $\mathbf{k}$ and $\mathbf{k'}$, respectively, the unit vector $\hat{\mathbf{n}}$, the polarization vector $\mathbf{P}$, and the angles θ and ϕ.

The vector analyzing power $A_n(\theta)$ for transverse electron beam polarization along the $\hat{\mathbf{n}}$ axis is defined in a model independent way through [12]

$$A_n(\theta) = \frac{Tr\{M(\theta)\Sigma_n M^\dagger(\theta)\}}{Tr\{M(\theta)M^\dagger(\theta)\}}, \tag{6}$$

where M is the full amplitude for the electron-proton interaction, and Σ_n is a covariant spin operator for the incident electron polarized along the $\hat{\mathbf{n}}$ axis. A perturbative expansion of the amplitude M through second order gives

$$M = M_B + M_{2\gamma} + ..., \tag{7}$$

where M_B is the Born amplitude for the exchange of one virtual photon, and $M_{2\gamma}$ is the two photon exchange amplitude, as shown diagramatically in Fig. 2. Upon carrying through the spin algebra and traces of Eq. (6), and exploiting the fact that M_B is purely real, one obtains [12]

$$A_n = \frac{2M_B \Im\{M_{2\gamma}\}}{|M_B|^2} \tag{8}$$

to leading order. Thus, the vector analyzing power in elastic electron-proton scattering is directly proportional to the imaginary part of the two photon exchange amplitude.

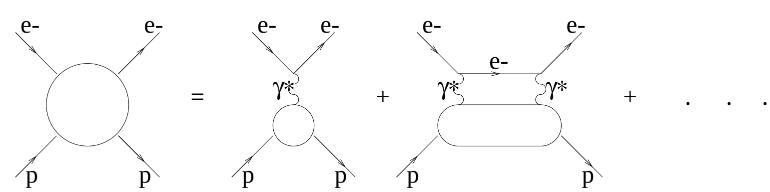

Figure 2: Perturbative expansion of the electron-proton scattering amplitude in terms of the number of virtual photons exchanged.

2.2 The Two Photon Exchange Amplitude: Calculations

Previous calculations of vector analyzing powers for low energy, spin 1/2 probes incident on heavy nuclei have been performed using the original derivation of Mott [13], where the energies are low enough to assume that the nucleus is simply a point charge of magnitude Ze. The analyzing powers calculated in these cases are much larger than the vector analyzing power for electron-proton scattering considered here, and this is commonly exploited as a means to measure the polarization of low energy electron beams ($\sim$ 100 keV) with the use of "Mott" polarimeters [9]. In the kinematics proposed here, the electron energies of 424, 585, and 799 MeV are much larger than the energies used for Mott polarimetry, and the proton target has the smallest possible Z so that Coulomb effects are at a minimum, suggesting that new theoretical treatments of the vector analyzing power in terms of the two photon exchange amplitude are required.

Previous calculations of the two photon exchange amplitude are also somewhat limited. It was originally noted [14] that two photon exchange amplitudes were sensitive to the nucleon polarizability, but many approximations used in that work led to only an estimation that the contribution of the two photon exchange amplitude to the total electron-proton scattering process was of order 0.5% for intermediate energy electron beams ($\sim$400 MeV), and increased with increasing beam energy. Further work involved a low momentum transfer theorem for two photon exchange processes with hadronic systems [15], where it was also proposed that an observable which would provide straightforward evidence for the existence of two photon exchange amplitudes was the cross section asymmetry for lepton-hadron vs. antilepton-hadron scattering. Other suggestions for the observation of two photon exchange effects are for high momentum transfer data in elastic electron-deuteron scattering [16, 17]. In a model for this process, the dominant contribution is one in which the electron exchanges virtual photons with each nucleon separately, and therefore represents a more collective process in which the internal structure of the individual nucleons is not fully probed. This two photon exchange mechanism is expected to decrease much more slowly with momentum transfer than one photon exchange processes, so that its effects should be observable at high enough momentum transfers ($\sim$3-5 (GeV/c)^2).

Very recently, there has been much renewed interest in the two photon exchange amplitude arising from two separate theoretical publications which included this contribution in attempts to resolve the experimental descrepancy between Rosenbluth and polarization transfer techniques used to extract the ratio of the proton's electric to magnetic form factors G_E^p/G_m^p. In the first [18], the contribution of the two photon exchange amplitude is included in a general analysis, where a phenomenological fit of the real part of this amplitude and the ratio of $|\tilde{G}_E|/|\tilde{G}_M|$ is performed to reproduce the experimental data for both techniques. This demonstrated that the Rosenbluth technique data received a sizeable correction due to the two photon exchange amplitude at relatively high Q^2, while the polarization transfer data did not, helping to resolve the descrepency between the two. In the second work [19], the real part of the two photon exchange amplitude is evaluated as a radiative correction to the *ep* cross section, where the intermediate state is taken as a nucleon (the "elastic" contribution, which we discuss below), the results of which give the correct sign and magnitude to resolve a large part of the descrepency between the two experimental techniques.

Calculations of the vector analyzing power in *ep* elastic scattering have been performed [4] in the resonance region to compare with the SAMPLE and Mainz data, where the two photon exchange amplidude is expressed as a diagramatic expansion as shown in Fig. 3. In the first term of this expansion, free proton form factors are used at the photon-proton vertices, and a free proton propagator is assumed in the intermediate proton state (the "elastic" contribution). Higher order terms in this expansion include intermediate state resonances (e.g. the Δ^+), and the creation of intermediate state virtual mesons, which become possible if the incident virtual photon energy crosses the pion threshold. For these higher order terms, $\gamma N\Delta$ or $\gamma N\pi$ coupling constants must be used at the photon-nucleon verteces, and Δ or nucleon and π propagators must be used in the intermediate state, making them more complicated and model dependent. As a first step toward developing the theoretical machinery to handle the intermediate states in the two photon exchange diagram, and box diagrams in general, calculations were performed [4] which included the elastic contribution (the first term in the expansion in Fig. 3), and only the Δ^+ resonance as the inelastic contribution (the fourth term in the expansion in Fig. 3). The main results of that work were that the elastic contribution was small at both energies studied (of order a few ppm), while the Δ^+ contribution was small at lower energies but became the dominant contribution to the vector analyzing power at larger energies. This is consistent with the idea that the more energy available in the intermediate state, the more particles or resonances can be created. For the 200 MeV case, the amount of energy available is just above pion production threshold, and not enough to excite the proton to the peak of the Δ^+ resonance, while for the 855 MeV case, there is plenty of energy available in the intermediate state to excite the Δ^+. In fact, as the beam energy increases, more and more intermediate state resonances can contribute, although they may contribute with different signs.

These calculations in the resonance region have since been refined [4] to include all πN intermediate states, both resonant and non-resonant, up to an invariant mass of 2.0 GeV. Shown in Fig. 4 are these calculations at a variety of energies spanning the energies of the proposed measurements, along with the data from Ref. [7]. The curves for each of these energies are separated into the elastic contribution (dashed line) where only the nucleon intermediate state is considered, and the inelastic contribution (dot-dashed line), and the total (solid line). Some observations regarding these calculations are worthy of note. First, in each case the inelastic contributions dominate over the elastic contributions at all center of mass scattering angles except near 0° and 180°. Secondly, the predicted magnitude of the vector analyzing power at its peak reaches a maximum at a beam energy somewhere between 0.3 and 0.57 GeV, and decreases with increasing beam energy, suggesting that for higher beam energies a transition to theoretical treatments in terms of partonic degrees of freedom and generalized parton distributions may be more appropriate (we discuss this further below). Also, in comparing the calculations at 855 MeV which include all πN intermediate states (those in Fig. 4) to those which only include the Δ^+ intermediate state, it is seen that the full πN inelastic treatment in the resonance region significantly affects the predicted value of this observable as compared with only including the Δ^+ inelastic contribution, and that contributions from other resonant and non-resonant intermediate states come in with differing signs to that of the Δ^+ intermediate state. This suggests that the theoretical methodology for treating box diagrams in general must be well understood for predicting observables involving such diagrams. This has implications for weak interaction box diagrams (such as a $\gamma - Z_0$ box diagram) which contribute as radiative corrections to parity violating electron scattering observables. Finally, we note that the kinematics of the G0 backward angle running, in which beam energies of 0.424, 0.585, and 0.799 GeV are used where electrons are detected at laboratory angles of 110°, with corresponding center of mass angles of 126.2°, 129.9° and 133.9°, indicate that the vector analyzing powers for these measurements are very near the maxima of the predicted values for these observables. Thus, these measurements will be maximally sensitive to inelastic intermediate state contributions to the two photon exchange amplitude.

Another recent set of calculations for observables involving the two photon exchange amplitude [20] investigates both beam and target single spin

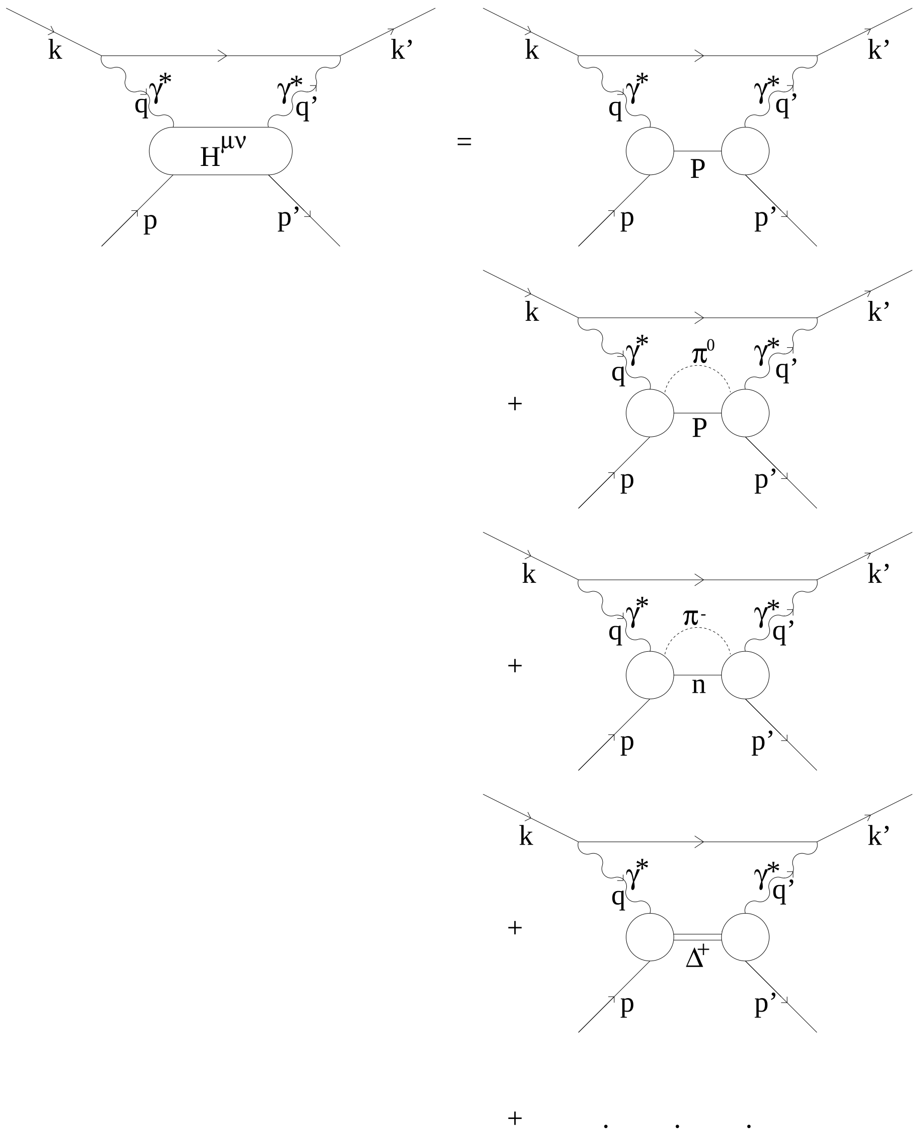

Figure 3: Perturbative expansion of the two photon exchange amplitude in terms of the number of intermediate state particles allowed through momentum conservation at the electron-virtual photon verteces.

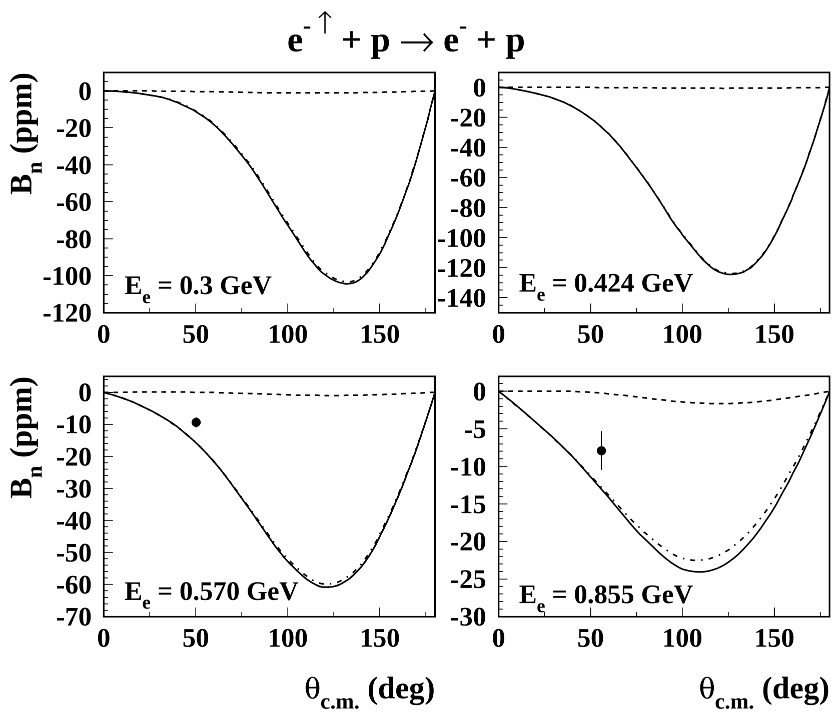

Figure 4: Calculations of the vector analyzing power as a function of center of mass scattering angle for beam energies of 300, 424, 570, and 855 MeV. Also plotted are the data from Ref. [7] at 570 and 855 MeV. Details of the calculations are described in the text.

asymmetries for somewhat higher energies and momentum transfers, and makes a connection to generalized parton distributions. In this work, the available phase space for the virtualities of the two virtual photons involved is investigated for a beam energy of 5.0 GeV and overall momentum transfers of $1.0 \leq Q^2 \leq 6.5$ (GeV/c)^2. The "elastic" contribution again considered free proton form factors at the photon-proton verteces and proton propagators in the intermediate state, while the "inelastic" contribution was handled in a somewhat different manner than a perturbative expansion as discussed above. Given the higher beam energy and overall momentum transfers, the inelastic contribution was based on a model inspired by the deep inelastic scattering region. A non-forward Compton amplitude with two virtual photons from Ref. [21] was used to form a model for the non-forward structure functions based on interpolation of standard inclusive structure functions and additional Q^2-suppression arising from t-dependence of generalized parton distributions. The inclusive structure functions were empirically fit to deep inelastic data. The main results of this work were that i) although the beam and target single spin asymmetries are both proportional to the imaginary part of the two photon exchange amplitude, they are indeed independent observables, and ii) large virtualities of both virtual photons was important.

More recently, another set of calculations of the vector anlayzing power makes a direct connection between this observable and the generalized parton distributions [5]. Although the momentum transfers considered in that work are somewhat higher than those considered here, it does demonstrate that a connection exists between the vector analyzing power and generalized parton distributions. These calculations can, in principle, be extended to lower beam energies and momentum transfers to compare with the proposed measurements, and to compare with calculations based on resonance region treatments of the two photon exchange amplitude intermediate states.

3 Experimental Apparatus – G0 Backward Angle Configuration

The G0 spectrometer and detector system has been documented at length [8, 22], so we only highlight the features of this system which make it ideally suited for the measurements proposed here. This system has been designed specifically to measure small ($\sim$ ppm) yield asymmetries in longitudinally polarized electron scattering, with high luminosity capabilities and a large acceptance detector. Many of the design features have taken into account possible false asymmetries and systematic effects, which will be no larger than 5% of the measured parity violating asymmetry. Included in this design is an axially symmetric geometry.

For asymmetry measurements using longitudinally polarized electrons, there is no preferred axis in space that is transverse to the beam direction. Thus, at a given polar scattering angle θ relative to the beam direction, the parity violating asymmetry measured at any azimuthal angle ϕ should be the same, neglecting systematic effects. Many first order systematic effects associated with spin-dependent beam properties can therefore be minimized by averaging the measured asymmetries over the entire azimuthal dependence. For a transversely polarized beam, on the other hand, the preferred axis in space is now transverse to the beam direction, and corresponds to the beam polarization direction. The axial symmetry of this apparatus, along with its full ϕ coverage, allows for a data analysis technique which exploits this symmetry, as was done for the vector analyzing power measurements using a 200 MeV beam with the SAMPLE apparatus, and using 570 MeV and 855 MeV beams with the A4 apparatus, and a 3.0 GeV beam using the G0 forward angle appratus. Based purely on geometry, the physics asymmetry generated by transversely polarized electrons must follow a sinusoidal dependence in the azimuthal angle ϕ relative to the beam polarization direction. With eight separate but identical detector packages positioned symmetrically around the beam axis in the G0 system, one can extract the physics driving this dependence with an excellent check of the internal consistency of the data through the χ^2 function in Eq. (4) which describes how well the data follow this dependence.

As part of a program to understand systematic effects for the G0 forward angle measurements, some time was spent measuring the vector analyzing power for elastic electron-proton scattering in the forward angle G0 kinematics in order to constrain this contribution to the parity violating asymmetry. Thus, the G0 apparatus has demonstrated its ability to measure ppm transverse asymmetries as well as ppm parity violating asymmetries.

4 Kinematics and Rates

The G0 backward angle measurements will be performed by detecting elastically scattered electrons at backward angles ($\theta_e \sim 110^{\circ}$) using a combination of FPD's and another set of detectors mounted at the exit of the spectrometer, the Cryostat Exit Detectors (CED's). In the backward angle mode of running, it is the elastically scattered electrons which are detected, where a fixed scattering angle fixes the relationship between the incident beam energy and the Q^2 value for these events. Thus, three different beam energies will be used to provide a Q^2 range for elastic scattering of $0.3 \leq Q^2 \leq 0.8$ (GeV/c)^2.

For the backward angle measurements, one beam energy results in a single value of Q^2 for the entire elastic scattering locus of electrons accepted into the detectors. In Table 1 we summarize the kinematics and rates for these events. These rates have been calculated assuming an electron beam of average intensity 80 μA incident on a 20 cm LH_2 target.

Beam Energy (GeV)	$Q^2_{el.}((GeV/c)^2)$	θ_{CM}	Rate (MHz)
0.424	0.3	126.2	2.04
0.585	0.5	129.9	0.72
0.799	0.8	133.9	0.20

Table 1: Elastic kinematics and rates for the G0 backward angle measurements, integrated over all eight sectors of the system.

5 Beam Time Estimates and Statistical Uncertainties

5.1 Beam Time and Statistics

From the elastic scattering rates calculated in the previous section, we can determine how much beam time would be required to achieve a given statistical uncertainty on these proposed measurements.

The asymmetry for each detector will be determined from experiment as

$$A = \frac{1}{|\mathbf{P}|}\frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}, \tag{9}$$

where $N_\uparrow$ and $N_\downarrow$ are the number of elastically scattered particles detected for the beam polarization $\mathbf{P}$ parallel and antiparallel to $\hat{\mathbf{n}}$, respectively. For small asymmetries, $N_\uparrow \approx N_\downarrow$, so that the uncertainty in this quantity is given by

$$\delta A = \frac{1}{|\mathbf{P}|} \frac{1}{\sqrt{N}}, \tag{10}$$

where $N \equiv N_\uparrow + N_\downarrow$ is the total number of elastically scattered particles seen in that detector, which can be estimated for a given amount of time T as $N = Rate \cdot T$. Thus, the required time is found from

$$T = \frac{1}{|\mathbf{P}|^2} \frac{1}{Rate} \frac{1}{\delta A^2} \tag{11}$$

for a desired uncertainty δA at a given beam polarization $|\mathbf{P}|$.

Using the rates determined above, assuming a beam polarization magnitude of $|\mathbf{P}| = 70\%$, and setting a goal for the desired statistical uncertainty of 3 ppm, we obtain the following beam time requirements for the backward angle mode of running, listed in Table 2. Because the largest proposed energy of 799 MeV is close to the energy of 855 MeV for which a theoretical prediction exists [4], we use this prediction and set goal of a 10% measurement (or 3 ppm) of the maximum effect expected for these kinematics.

Beam Energy (GeV)	$Q^2_{el.}$ $((GeV/c)^2)$	Time (days)
0.424	0.3	0.7
0.585	0.5	1.8
0.799	0.8	6.5
Total		9.0 days

Table 2: Beam time estimates to achieve a 3 ppm statistical uncertainty on the vector analyzing power in elastic electron-proton scattering for the backward angle G0 kinematics assuming a beam polarization magnitude of $|\mathbf{P}| = 70\%$.

5.2 Constraints on A_{PV}

Although previously unmentioned throughout this proposal, measurements of the asymmetries due to transverse polarization necessarily impose constraints on the contribution of this parity conserving quantity to the parity violating asymmetries to be measured using the G0 apparatus. The beam polarization can be oriented nearly longitudinally as it enters Hall C, but there is an uncertainty in its absolute direction, i.e. there could be small transverse components of the beam polarization. As previously outlined in the formalism for the vector analyzing power, these transverse components will lead to a parity conserving contribution to the measured asymmetry. Whatever the size of this effect, a measurement of this quantity will allow for a correction to the parity violating asymmetry from this contribution.

If we conservatively assume that the direction of the beam polarization as measured in Hall C can be determined to $\delta\theta_{pol} = \pm 3°$, then the maximum contribution from the transverse vector analyzing power to the longitudinal parity violating asymmetry measured with the beam polarization oriented nearly longitudinally is given by

$$A_n^L = \frac{\sin 3°}{\sin 90°} A_n \tag{12}$$

where A_n is the vector analyzing power discussed throughout this proposal and A_n^L is the contribution from A_n to the longitudinal asymmetry. Thus, the uncertainty in this contribution is

$$\begin{aligned} \delta A_n^L &= \tfrac{\sin 3°}{\sin 90°} \delta A_n && (13) \\ &= 0.05 \delta A_n. && (14) \end{aligned}$$

For the backward angle measurements, then, assuming a 3 ppm uncertainty is obtained on the vector analyzing power as proposed here, the maximum uncertainty in the contribution to A_n is $\delta A_n^L = 0.05 \times 3$ ppm $=$ 0.15 ppm. The smallest expected parity violating asymmetry for the backward angle measurements is 18 ppm at $Q^2 = 0.3$ (GeV/c)^2, so the relative uncertainty in the contribution from the vector analyzing power is ∼0.8%, which is negligible compared to the goal of 5% relative uncertainty from all systematic effects.

6 Transverse Beam Polarization

6.1 Beam Energies and Polarizations

In any experiment involving the measurement of small asymmetries, it is desirable to have as many systematic checks on the measurement technique as possible. For the SAMPLE [23, 24], HAPPEX [25], and Mainz A4 [7] parity violation measurements, as well as for the G0 [8] measurements, one such systematic check is the insertion and removal of a $\lambda/2$ plate in the polarized laser beam used to generate the polarized electron beam. This has the effect of manually reversing the electron beam polarization relative to all electronic signals, so any real physics asymmetry must reverse sign in a correlated way. As demonstrated in the vector analyzing power measurements at $Q^2 = 0.1$ (GeV/c)^2 [6], another systematic check on the measurement technique was to orient the transverse beam polarization direction in two orthogonal orientations for two different sets of measurements. This provided another check of internal consistency in the data, in that the sinusoidal dependence of the measured asymmetries changed phase by 90° from one data set to the other. Ideally, for the measurements proposed here, this systematic check would also be included. We are sensitive, however, to Jefferson Laboratory's commitment to running multiple experiments simultaneously. If the beam polarization were oriented vertically ($\phi = 90°$ as in Fig. 1), then it would not be possible to deliver longitudinally polarized beams to the other experimental halls. It is possible, however, to deliver an electron beam with maximum transverse polarization in Hall C, and still have relatively large longitudinal polarization into Hall's A and B. Thus, for these proposed measurements of vector analyzing powers, we would only request transverse polarizations with $\phi = 0°$ or 180° (as in Fig. 1).

To determine what angle the beam polarization must be oriented at the polarized source to generate maximum transverse polarization in Hall C at the appropriate beam energies used for the G0 backward angle measurements, we used the CLAS spin calculator found at http://clasweb.jlab.org/cgi-bin/spin-rotation/spin-rotation.pl. The beam energies to be used for the G0 experiment are fixed by the choice of Q^2 values to be studied. In Table 3 we list the beam energies required for the G0 backward angle measurements, the single pass LINAC energy and number of passes to Hall C which will generate those beam energies, and the polarization angle at the polarized source required to achieve 0% longitudinal polarization (corresponding to maximum transverse polarization) in Hall C. The ability to generate 0% longitudinal polarization in Hall C has been demonstrated during successful mini-spin dances performed during the forward angle G0 running, in addition to the 4 days of running with transversely polarized beam using the G0 forward angle setup.

With the number of passes to Hall C, the LINAC energy, and the source polarization angle fixed, the number of allowed passes, energies, and polarization directions to the other halls is fixed. We use the spin calculator

Beam Energy (GeV)	LINAC Energy (GeV)	Passes to Hall C	$\theta_{source}(^\circ)$
0.424	0.201	1	35
0.585	0.277	1	15
0.799	0.378	1	166

Table 3: Beam and single pass LINAC energies required for the G0 backward angle measurements, along with the polarization direction at the polarized source to generate maximum transverse polarization in Hall C.

to determine what energies and relative polarizations would be available to Halls A and B with the constraints in Table 3, and list the results in Table 4.

Hall C E(GeV)	Passes(A)	E(A) (GeV)	$P_L/\|\mathbf{P}\|$(A)	Passes(B)	E(B) (GeV)	$P_L/\|\mathbf{P}\|$(B)
0.424	2	0.825	-0.09	2	0.826	-0.97
	3	1.227	0.91	3	1.227	-0.63
	4	1.629	0.97	4	1.629	-0.57
	5	2.030	0.94	5	2.030	-0.89
0.585	2	1.139	-0.32	2	1.139	0.98
	3	1.693	-0.49	3	1.693	0.91
	4	2.247	-0.74	4	2.247	0.85
	5	2.800	0.53	5	2.800	-1.00
0.799	2	1.555	-0.95	2	1.555	0.41
	3	2.311	-0.38	3	2.311	0.63
	4	3.068	-0.96	4	3.068	0.40
	5	3.825	0.75	5	3.825	0.25

Table 4: Available beam energies and relative polarizations for Halls A and B subject to the constraints given in Table 3.

6.2 Hall C Polarimetry

At present, the longitudinal component of the beam polarization in Hall C is measured with a Moller polarimeter, in which a superconducting magnet generating a large magnetic field ($\sim$ 3.0 T) is used to polarize an iron foil target along the beam direction. For the transverse asymmetry measurements proposed here, some knowledge of the transverse components of the beam polarization entering Hall C will be required. While this device, as it exists, can determine where the longitudinal component is zero, and therefore determine that the beam is polarized transversely, the error in extracting the magnitude of the transverse polarization is large, even though the statistical accuracy for this measurement is the same as that for the longitudinal polarization measurements. Better precision could be obtained if it were possible to measure one transverse component, P_x^B, of the beam polarization.

For Moller scattering of beam electrons of polarization $\mathbf{P}^B$ scattering from target electrons of polarization $\mathbf{P}^T$, the measured asymmetry for relativistic electrons and at 90° center of mass scattering angle is given by

$$A = -\frac{1}{9}\left[\frac{1}{1+B/S}\right][7P_z^B P_z^T - P_y^B P_y^T + P_x^B P_x^T], \tag{15}$$

where B/S is the ratio of the background to real signal for Moller scattering. Thus, if it were possible to polarize the Moller target electrons along the x direction, while keeping the z target polarization component at zero, then a better determination of P_x^B would be possible. To achieve this, some upgrade to the existing Moller polarimeter in Hall C will be required. The installation of a set of Helmholtz coils along the x axis with its center at the Hall C Moller target would be sufficient to provide the necessary transverse component of the target polarization. There are plans to upgrade the Hall C Moller polarimeter to include the ability to measure one transverse component of the beam polarization. Design efforts will begin in Summer 2004, and the upgrade should be complete in early to mid 2005.

7 Backgrounds

During the backward angle mode of G0 running, it is the electrons which are detected. Because the electrons are relativistic, time of flight information alone cannot distinguish between elastically and inelastically scattered electrons. The identification of these two types of events will be possible through the use of a second set of detectors mounted at the exit of the G0 cryostat (CED's) used in coincidence with the FPD's, which allows for a measurement of the scattered electron momentum and scattering angle. With the use of coincidence logic circuitry, it will be possible to measure the yield asymmetries for both elastically and inelastically scattered electrons. Although there will be a small contribution to the elastic yields from inelastically scattered electrons, the inelastic asymmetry will be measured simultaneously, allowing for a correction to the elastic asymmetries from these events.

Another source of background for these measurements will be π^-'s created during two pion electro and photoproduction from the protons in the LH_2 target and single π^- production on the neutrons in the aluminum target end caps. Although these particles also cannot be eliminated by time of flight information, they can be eliminated by particle identification techniques. To achieve this, an aerogel Čerenkov detector will be installed between the CED and FPD arrays, with threshold adjusted to only trigger on electrons, and thus the π^-'s will be hardware rejected.

For the inelastic asymmetries measured with longitudinally polarized electrons at backward angles, i.e. the parity violating asymmetry in single pion electroproduction [26], there has been a significant amount of theoretical effort to predict the size and Q^2 dependence of this asymmetry. In contrast, there is no theoretical guidance as to the size or dependence of the asymmetry in inclusive single pion electroproduction for transversely polarized electrons. Nonetheless, with the apparatus to be used for the G0 backward angle running, we will be able to measure this asymmetry across the Δ resonance with approximately the same precision as the elastic scattering asymmetry using transversely polarized electrons, and the same correction technique for the elastic parity violating asymmetries can be used for the vector analyzing powers in elastic electron-proton scattering.

8 Summary and Requested Beam Time and Support

The vector analyzing power in inclusive elastic electron-proton scattering is a time reversal odd observable that must vanish in the single photon exchange approximation, and is directly proportional to the imaginary part of the two photon exchange amplitude. Recent calculations tie this observable to resonance region treatments of box diagrams and generalized parton distributions.

With the development of the technology to measure small parity violating effects in polarized electron scattering, and the ability to produce transversely polarized electron beams at high energies, these transverse effects are now amenable to measurement. We propose vector analyzing power measurements in elastic electron-proton scattering using the G0 apparatus in its backward mode of running. The high luminosity capabilities of this system, along with its large acceptance detector system, allow for statistically meaningful results to be obtained in a relatively short amount of beam time. We request 0.7, 1.8, and 6.5 days of transversely polarized beam added to the existing allocated beam time for the G0 backward angle measurements for Q^2 values of 0.3, 0.5, and 0.8 $(\mathrm{GeV/c})^2$, respectively, which will be used to measure the vector analyzing power in inclusive elastic electron-proton scattering. The G0 backward angle apparatus can be used for these measurements with no modification, and transversely polarized beams have been successfully delivered to Hall C during the G0 forward angle running.

Finally, in order to more precisely determine the transverse components of the beam polarization, we request a minor upgrade to the Hall C Moller polarimeter to include the capability of measuring one transverse beam polarization component. This is achievable with the inclusion of Helmholtz coils with an axis oriented horizontally with respect to the beam direction. This effort will begin in Summer 2004, and will be complete in early to mid 2005.

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